REP-RATED, HIGH COULOMB RAIL SWITCH DEVELOPMENT*

by

E. Chu, J. Graham, E. Lopez, K. Salisbury,
M. Scott, D. Ralph, A. Cole, G. Barton
Maxwell Laboratories, Inc.
8888 Balboa Avenue
San Diego, California 92123

and

D. Hall, K. Hackett, W. Baker
Air Force Weapons Laboratory
Kirtland AFB, New Mexico 87117

Abstract

Compact, high power, rep-rated, pulsed power systems require high voltage, high coulomb, and low inductance switches. In this paper, we describe the development effort for a rep-rated, rail-electrode spark-gap switch. The design of the rep-rated switch is based on the tried and proven single shot, rail switches found on the 9 MJ, SHIVA STAR system at AFWL. The electrodes have been modified to facilitate gas flow and switch recovery time. Rep-rate testing of the switch is accomplished by sequentially discharging multiple capacitor banks each capable of storing up to 40 kJ. The initial design performance goal for this rep-rated rail switch is 10-100 Hz, 100 kV, >1 Coulomb per shot. This paper discusses the design, the triggering, and the preliminary test results of the switch.

Introduction

By virtue of their geometry, rail switches have been widely used to provide low inductance switching in many single shot pulsed power systems that involve high peak currents and large coulomb transfer. An example is the 9 MJ SHIVA STAR system currently in operation at the Air Force Weapons Laboratory. The SHIVA STAR rail switch is a pressurized three electrode spark gap switch made up of two brass electrodes and a tungsten-copper field distortion trigger electrode originally developed by Maxwell in 1973. By applying a fast rising voltage pulse (e.g. >10 kV/ns) to the trigger electrode, multiple arc channels can be established between the main electrodes. The typical inductance of the 120 kV rated SHIVA STAR rail switch is 25 nH or less. By connecting several switches in parallel, an extremely low inductance capacitor bank can be constructed. For the SHIVA STAR, there are 36 capacitor banks feeding six solid dielectric transmission lines arranged in a star configuration. Each capacitor bank has four parallel rail switches giving a total of 144 switches in the entire system. Peak current achievable with the SHIVA STAR has been demonstrated in excess of 60 MA.

Repetitive operations of the rail switches to date have been at relatively low voltage and low peak current. The rep-rated, high coulomb rail switch development effort that we are reporting in this paper addresses the requirement to switch tens to hundreds of kilo-joules in 1 microsecond at voltages up to 100 kV and at repetition rates up to 100 pulses per second. Because of its large operational data base, the single shot SHIVA STAR rail switch our design is used as the basis for the design of the rep-rated, high coulomb rail switch.

Rep-rated Rail Switch Design Considerations

Several factors have received the attention during our design of the rep-rated, high coulomb rail switch. They are: peak current, repetition rate requirements, and insulator life considerations. These critical factors are discussed in the following paragraphs.

The nominal peak current requirement of the rail switch is in the range of 200 to 300 kilo-amperes. Many of the anticipated applications of the switch will also require paralleling of several switches. As a result, the maximum fault current requirement for each switch could be a large fraction of a mega-ampere. To ensure the mechanical integrity of the switch at this high current level, the switch housing design of the single shot SHIVA STAR rail switch is adopted as its maximum fault current capability has been established to be over 750 kA. The rep-rated switch housing consists of a cast base and a machined cover. The base is made out of fiber glass reinforced epoxy whereas the cover is made of acrylic. The main electrodes are brass and are mounted directly on the base. These electrodes are provided with slotted holes to permit adjustment of parallelism and spacing of the main electrodes to the trigger rail. Typical separation between the main electrode is 0.85 inch. The trigger electrode is located between the main electrodes at 0.56 inch from the high voltage electrode. A picture of the switch housing is depicted in Figure 1.

To select a switch design approach that meets the rep-rate requirements, we note that the dielectric recovery time after current conduction is a function of the initial discharge characteristics and the processes taking place in the discharge channel. During switch conduction, energy is continuously deposited in the arc channel to overcome losses due to recombination, diffusion, conduction, convection, and radiation. After current zero, these energy loss mechanisms become responsible for the recovery of the gas dielectric. During the early recovery period when the gas is ionized and the electrical conductivity is high, re-application of voltage across the switch will provide power input to the gap. The recovery process

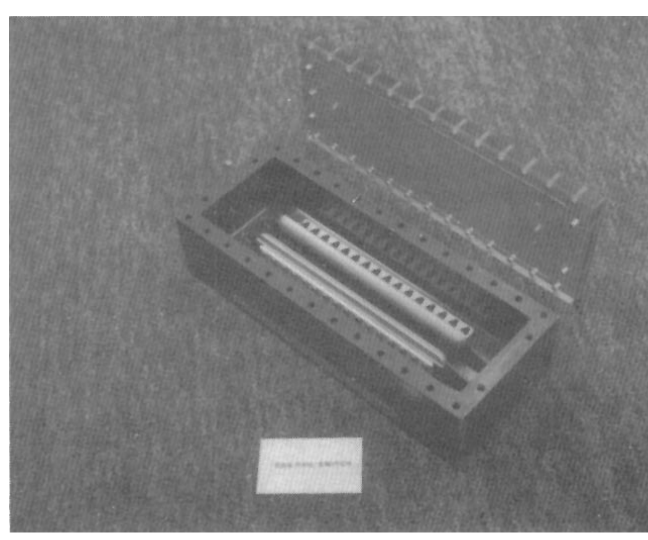

Figure 1. Picture of the switch housing used for the Rep-Rated Rail Switch development.

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14. ABSTRACT
Compact, high power, rep-rated, pulsed power systems require high voltage, high coulomb, and low inductance switches. In this paper, we describe the development effort for a rep-rated, railelectrode spark-gap switch. The design of the rep-rated switch is based on the tried and proven single shot, rail switches found on the 9 MJ, SHIV A STAR system at AFWL. The electrodes have been modified to facilitate gas flow and switch recovery time. Rep-rate testing of the switch is accomplished by sequentially discharging multiple capacitor banks each capable of storing up to 40 kJ. The initial design performance goal for this rep-rated rail switch is 10-100 Hz, 100 k V, > 1 Coulomb per shot. This paper discusses the design, the triggering, and the preliminary test results of the switch.

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will be interrupted if the power input exceeds the channel losses. In the later stage of recovery when little or no ionization remains, the arc channel evolves into a high temperature, low-density gas column in which reignition occurs by Paschen breakdown. Dielectric recovery of the gap will continue as the high temperature, low density gas column decay through the diffusion, convection, and conduction processes within the gap. For a static filled gas spark gap, full dielectric recovery may never occur following a high current discharge. This is because the electrode material vaporized at the arc roots during current conduction will cause degradation of the gas dielectric strength. If one ignores the degradation due to change in gas composition, the recovery time is about 20 milliseconds for most gas dielectric and less than 100 milliseconds in essentially all cases. A simple approach to extend the rep-rate capability of a static fill spark gap beyond that governed by the recovery time is to operate the switch at a pressure that is substantially above the self break value for a given voltage. To this end, we elected to operate the rep-rate, high coulomb rail switch at three times below the self break voltage of the switch.

To minimize the plating out of the vaporized electrode material on the switch insulator, a gas flow approach patterned after the switch developed by Buttram and Rohwein of Sandia[1] is adopted. Two gas plenums are built into each main electrode as shown in Figure 2. A set of 47 gas jets connected to the lower plenum provides laminar gas flow over the surface of the insulator that is directly exposed to the main discharge. The gas then carries the arc by-products as it sweeps through the inter-electrode region. The maximum flow rate provided by these gas jets is approximately 20 scfm corresponding to a velocity of 3.1 ft per second through the inter-electrode region. Connecting to the upper gas plenum in each electrode is a set of 36 high velocity jets with a gas exhaust velocity of 250 feet per second to ensure effective mixing of the arc by-products and the cooler ambient gas. The upper gas jets, in spite of a much higher gas velocity, have a gas flow rate a third of that of the laminar flow jets.

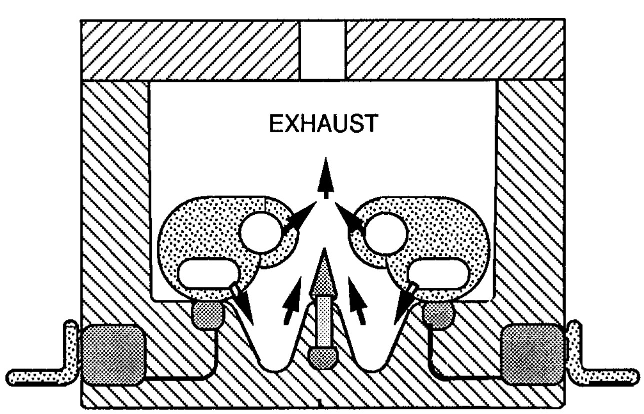

Figure 2. Schematic showing gas flow arrangement of the Rep-Rated Rail Switch.

Rail Switch Trigger Design

Since the rep-rated rail switch is designed to operate at a relatively high self break to operating voltage ratio, a much heftier trigger pulse is required to ensure multi-channel operation. To this end, a 100 pulses per second trigger generator capable of providing over +150 kV pulses with a typical rise time of 10 ns was constructed. The trigger generator consists of basically a three stage Marx generator charged to approximately 30 kV per stage. The 150 kV trigger voltage is achieved through impedance mismatch at the output end of coaxial cable that connects between the Marx generator and the switch trigger electrode. To provide the fast output risetime, a peaking capacitor and a self firing peaking switch combination is added to the output of the Marx. Charging of the Marx generator is done using a command resonant charging circuit consisting of a spark gap, an inductor, and a diode. A trickle charging voltage doubler circuit from the dc power supply will also maintain the Marx charging voltage as well as assuring a full voltage first pulse. Triggering of both the Marx generator and the command resonant charging spark gap is accomplished using a thyratron switched pulser. A simplified schematic of the trigger generator is shown in Figure 3.

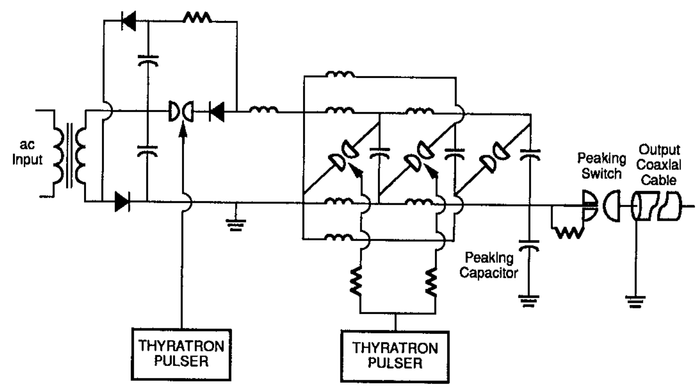

Figure 3. Schematic of the Rep-Rated Rail Switch Trigger Generator.

Switch Test Setup

Testing of the rail switch is accomplished using the test setup as shown in Figure 4. The test setup consists of a rep-rated capacitor bank made up of four 6 μF, 60 kV capacitors that are arranged in a series-parallel configuration to provide 6 μF of capacitance at 120 kV. The load is three 0.17 Ω high voltage Franklin resistors connected in parallel. Total series inductance (including the series inductance of the rail switch) in the high current discharge circuit is 265 nH.

Repetitive charging of the rep-rated capacitor bank is achieved by means of five single-shot capacitor banks discharged sequentially through resonant inductors. Because the output capacitance of each of these banks is the same as the rep-rated bank, the energy stored in the single-shot banks can be efficiently transferred to the rep-rated bank. By changing the delay time between the triggering of the single-shot banks, the rep-rated bank charging and discharging rate can be varied. Likewise, the charging voltage of the rep-rated bank can be varied by adjusting the dc charging voltage on the single-shot banks.

Experimental Results

Initial testing of the rail switch involves the charging of one of the five single-shot banks. Triggering the switch on the charged single-shot bank initiates the resonant energy transfer process from the single-shot bank to the rep-rated bank. The rail switch on the rep-rated bank is then triggered at the peak of the rep-rated bank charging voltage waveform. Figure 5 shows the rep-rated bank charging voltage, and the discharge current. With an initial charging voltage of ±50 kV on the single-shot bank (corresponding to 30 kJ of stored energy), the peak rail switch current is 316 kA.

Because of the absence of fast control circuits that would crowbar the single-shot banks in the event of a fault, the testing of the rail switch was conducted cautiously in order to limit the maximum fault energy that may damage the rail switch. After

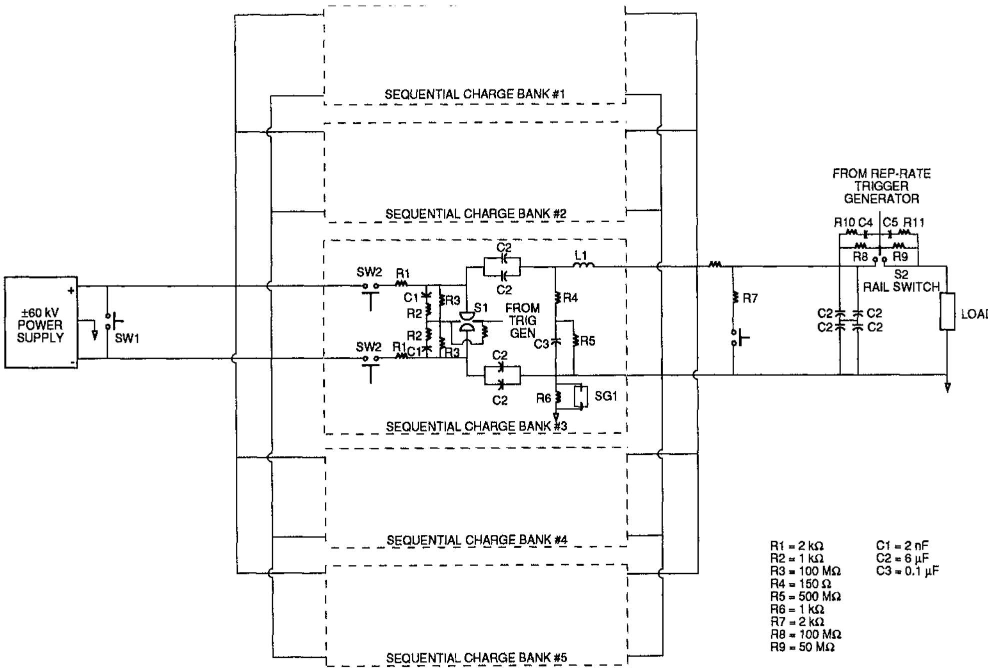

Figure 4. Schematic of the test set up for switch testing.

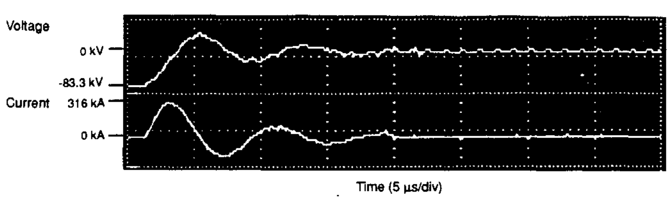

Figure 5. Waveforms showing the voltage and discharge current of the Rep-Rated Capacitor Bank.

initial testing using only 1 single-shot capacitor bank, a second bank was added and charged simultaneously with the first. Double pulse testing was started at 1 Hz (i.e. a delay time of 1 second between firing of the first and second single-shot bank) and at a charging voltage of ±25 kV on the single-shot banks. The charging voltage was increased from ±25 kV in steps of 5 to 10 kV until the charging voltage reaches 50 kV. At each voltage step, the number of pulses was built up slowly from 2 to 5. This was done to assure that the maximum amount of energy that will discharged through the rail switch is limited to only the amount of energy stored in one single-shot capacitor bank in the event that the rail switch failed to recover as a likely result of contaminated gas accumulation. This whole process is then repeated for higher pulse repetition rates. Maximum repetition rate that we have achieved is 50 pulses per second with an

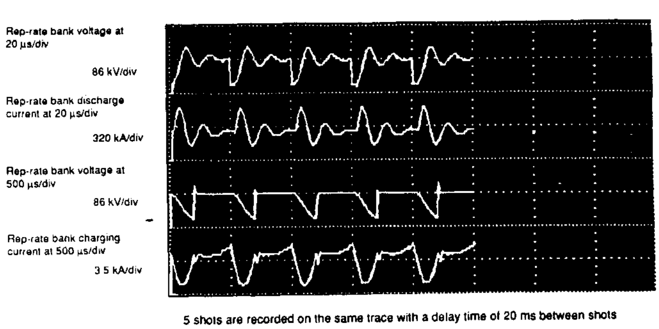

Figure 6. Waveforms showing successful operation of the Rail

initial charging voltage of ±40 kV on the single-shot banks. Figure 6 shows the various voltage and current waveforms recorded using a set of computer controlled transient digitizers. The waveforms associated with each successive pulse are displayed in sequence on the horizontal axis in Figure 6.

At 100 pulses per second, the transfer switch associated with the first single-shot capacitor bank did not recover its dielectric strength in time for the firing of the second bank. As the result, part of the energy stored in the second part was transferred to the first bank resulting in a lower charging voltage across the rep-rated bank.

Although the maximum repetitive operation capability of the high coulomb rail switch has not been exploited, these test results have clearly demonstrated that rep-rate much higher than what one would expect based on gas flow considerations can be realized. At the end of these test sequences, the rail switch was disassembled from the test set-up. Close examination of the switch shows that both the insulating switch base and switch cover remain very clean, particularly when they are compared with the switches that have seen similar coulomb duty on the SHIVA STAR capacitor banks. Our assessment of the improvement is a result of the gas flow that is implemented on the rep-rated switch.

Summary

We have reported the preliminary test results of the rep-rated, high coulomb rail-electrode switch development effort at AFWL. These results clearly indicate that the switch meets the design goals with relatively low gas flow rate. The switch has been tested at voltages up 83 kV, currents above 300 kA, and repetition rate up to 50 Hz. Higher repetition rate appears to be feasible since the 50 Hz reported was apparently limited by the test setup capability. The gas flow approach implemented appears to accomplish the task of maintaining the insulators free from arc debris damages.

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[1]M. T. Buttram and G. J. Rohwein, "Operation of a 300 kV, 100 Hz, 30 kW Average Power Pulser," Proc. IEEE Thirteenth Pulse Power Modulator Symposium, Buffalo, NY, June 20-22, 1978, pp. 303-308.